LASER-DRIVEN ULTRA-RELATIVISTIC PLASMAS

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14. ABSTRACT
In this grant period this PI developed new research directions and made progress in his fundamental and application research done previously for AFOSR. This PI predicted a new optical effect whereby a media with slow spatial gradient of its characteristics is found to exhibit a universal wave pattern ('gradient marker') in a vicinity of the maxima/minima of the gradient (Ref [1]); it is common for optics, acoustics, and quantum mechanics. Among potential applications of this effect is contour-detection and tracing of large moving submerged objects in the ocean. In his recent review [2], this PI has continued his research in the extreme ultra-short pulses beyond attosecond domain, which he pioneered in his research for AFOSR long ago by proposing the way to generate so called 'zepto-second' pulses. In his paper [3], this PI predicted that an overdense plasma layer irradiated by intense light should exhibit dramatic nonlinear-optical effects due to a relativistic mass-effect of free electrons: highly-multiple hysteresises of reflection and transition,and emergence of immobile waves of large amplitude. Those are trapped quasi-solitons in the layer sustained by a weak pumping having a tiny fraction of their peak intensity once they have been excited first by higher power pumping. The phenomenon persists even in the layers with 'soft' boundaries, as well as in a semi-infinite plasma with low absorption. These effects could be used for laser fusion to deposit laser powermuch deeper into the fusion pallets;or for heating the ionosphere layers by a powerful radiation. This PI also continued (Ref. [4]) his study of laser-excited atomic nano-structures, which were predicted by him earlier in collaboration with his post-doc Volkov in the research under AFOSR grant. Two new research direction have been open by the PI recently: (1) fully QED/relativistic theory of light pressure of

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LASER-DRIVEN ULTRA-RELATIVISTIC PLASMAS

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1. Brief review of the research under the reported grant

The reported research by this principal investigator and his group was done under the AFOSR Grant #F49620-11-1-0123 *"Laser- driven ultra-relativistic plasma..."*, project period: 36 months (06/15/2011 -- 06/14/2014), with no-cost-extension for 6 months till 12/14/2014. The research of this PI and his group has been supported by AFOSR continuously for about 35 years by the end of the reported grant. During that period, under AFOSR support, this PI and his group authored or co-authored about 400 publications, among them 12 books and book contributions, 115 regular journal papers, one patent, and 29 conference proceedings; the rest are conference papers. In particular, under the reported AFOSR support, 19 new papers have been published or submitted for publication including 6 journal papers, 1 refereed conference proceeding paper, and 12 conference papers.

All the effects proposed under the reported AFOSR support are novel and have initiated new opportunities in the field. The work by this PI and his group is highly credited by the research community. According to "Google Scholar", the total number of citations of his work is beyond 4,700, and his h-index is 39. The recognition by the research community is also reflected by the Max Born Award of the Optical Society (OSA) received by him in 2005. He has been selected for this award for his outstanding contributions to physical optics, in particular for *"seminal contributions to nonlinear interface and optical bistability effects, hysteretic resonances of a single electron, and physics of sub-femtosecond pulses"*. This award is one of the most prestigious awards of the OSA; it was awarded to 34 researchers for the entire history of the OSA. He was also a recipient of highly prestigious Alexander von Humboldt Award for senior USA scientists, by the AvH Foundation of Germany (one year in 1996, with the 3-month extension in 2009),a and International Professorship, Kyoto University, Japan, (3 months) in 2006.

The major field of research interests of this PI can be loosely described as extreme non-linear optics targeting various phenomena and their applications at the edge of capabilities of contemporary science and technology. This also involves other related lines of research, including linear optics, and some effects in nature. Under the reported grant, a number of new results were obtained by this PI in those fields:

2.i. The theoretical discovery of a universal wave pattern ("gradient marker") in the vicinity of maxima or minima of the gradient of refractive index in optics and a similar feature in quantum mechanics.

2.ii. A systematic review of pilot ideas on the generation of electromagnetic (EM)-pulses much shorter than already available sub-femtosecond pulses, and elaborating inroads and venues into the physics of pulses much shorter than an attosecond (10^{-18} seconds), in particular the so called zeptosecond (10^{-21} seconds) and yoctosecond (10^{-24} seconds) pulses that may allow one to operate on QED and nuclear, as well as quark-gluon time plasma scales.

2.iii. Prediction of dramatic nonlinear-optical effects due to a relativistic mass-effect in an over-dense plasma irradiated by intense light: highly-multiple hysteresises of reflection and transition, and emergence of "standing" relativistic solitons of large amplitude, with large potentials for applications.

2.iv. Continuation of research on previously discovered by this PI and his post-doc, Dr. S. N. Volkov, under AFOSR support of "locsitons" in self-interacting atomic nano-lattices.

2.v. Pilot new research on QED/relativistic light pressure of blackbody radiation on free electrons in Compton domain of energies and temperatures, with applications in particular to controlled nuclear fusion.

2. Final technical report on the grant #F49620-11-1-0123
2.i. "Gradient marker" -- a universal wave pattern and its applications [1]

In his research under this grant, this PI made a theoretical discovery [1] of a universal wave pattern ("gradient marker") in the vicinity of maxima or minima of the gradient of refractive index in optics and a similar feature in quantum mechanics. This discovery can result in promising applications in technology, such as e. g. medical surface-wave ultrasound tomography, detection of the movement of near-shelf profiles of the bottom of oceans and rivers by space- or air-borne photography of the patterns of wind-driven gravitation waves, as well as contour detection and tracing of submerged large moving man-made objects in the ocean.

Wave patterns in inhomogeneous media or confining structures are of great interest to quantum mechanics (QM), optics and electrodynamics, acoustics, hydrodynamics, and chemistry. Examples include wave packets in atoms, Ghladny patterns in acoustics, EM resonator and waveguide modes, Anderson localization in disordered systems, soliton formation due to nonlinearity, including atomic solitons in bosonic gas, as well as giant waves near caustics, waves in chemical reactions, dark-soliton grids, "scars" in "quantum billiard", "quantum carpets" in QM potentials, nano-stratification of local field in finite lattices (two latter subjects were discovered by this PI and his group within AFOSR supported research), etc. In all of those, the presence of multi-modes or a broadband spectrum is a prerequisite for interference and pattern formation in inhomogeneous or confining structures.

In [1] it was shown, however, that a localized wave pattern -- an immobile single-cycle intensity profile -- can emerge in a single-mode wave in the vicinity of a minimum or maximum of the gradient of a QM potential or optical refractive index. The phenomenon is universal for both optics and QM, and for any other propagation described by a wave equation. What makes it unusual is that it emerges in media with no potential wells and only a smooth inhomogeneity yielding no reflection -- and is originated by a purely traveling wave with apparently no other modes to interfere with. We found, however, that this wave here generates a co-traveling but localized "satellite" of slightly different phase and amplitude resulting in "self-interference". The wave ideally is not trapped and carries its momentum and energy flux unchanged through the area. To a degree, the pattern mimics a 2nd order spatial derivative of the refractive index (or potential function); it would be natural to call it a "gradient (G) marker". In QM it may be most

pronounced for an above-barrier propagation of an electron in continuum over smoothly varying potential; in solid state it might emerge above the critical temperature for the Anderson localization to vanish. Even for a potential well, when the energy of electrons exceeds the ionization potential and there is no trapping, the G-markers emerge as the main nonresonant localized feature.

We used a standard plain wave equation with a refractive index, $n(\xi)$, slowly varying along the axis of wave propagation, x, where $\xi = xk_0$, and $k_0 = \omega/c = 2\pi/\lambda 0$ is the wave number in vacuum. Of the most interest here is the limit of adiabatically slow variation in space, when gradient parameter $\mu \sim (k_0 L n_{min})^{-1}$, where L is a spatial scale of inhomogeneity, is small, $\mu \ll 1$, which corresponds to a quasi-classical case in QM. The reflectivity R in this case vanishes, and reflection can be neglected by a large margin. Looking in general case for the wave equation solution in the 2-nd order WKB approximation as a traveling wave with slowly varying in space amplitude and phase, $E = [1 + \Delta(\xi)]\, exp(i \int n(\xi)d\xi)/\sqrt{n}$, where (unknown in the beginning) complex function $\Delta(\xi)$ reflects the higher order WKB approximation, and solving it for $\Delta(\xi)$, we found that that the correction $\delta I(\xi)$ to the wave intensity, $I \equiv n/E/^2$, is as

$$\delta I(\xi) = (n'/n^{3/2})'/4n^{3/2} \tag{1.1}$$

where "prime" stands for $d/d\xi$, which is an elegantly simple but non-trivial result. In the vicinity of a gradient peak, $\delta I(\xi)$ makes an asymmetric single-cycle shape, with its middle point shifted by by $O(k_0 L n_{min})$ toward the area with a lower refractive index (or higher potential); its higher (and positive at that) peak is also located in the same area, see Figs. 1 and 2. One can see that *** more or less mimics a second derivative of n. Equation (1.1) can also be obtained via quasi-classical approximation in QM, whereby one has to search for high-order corrections for the phase of c as a function of the classical momentum pC, after which it has to be translated into correction to intensity

Our numerical simulations of spatial dynamics of $\delta I(\xi)$ for an **arbitrary** parameter μ, showed results converging amazingly fast to an asymptotic analytical result for a G-marker intensity, Eq. (1.1), as soon as $\mu < \mu_{cr}$, where $\mu_{cr} = 0(1)$ was some critical parameter related to a specific spacial profile $n(\xi)$. Interestingly, a clean, distinct and strong G marker can be formed even up to $L = \lambda_0/2$.

We have also investigated G-marker formation by a potential well (or a refractive index plateau) by modeling it with an "up-and-down" double step. As expected, both "soft" walls form G-markers symmetric to each other. At $\mu > \mu_{cr}$ we observed oscillations, same as for a single wall for the same μ_{cr} , and ideally clean G-markers for $\mu < \mu_{cr}$, similar to a single gradient wall. The major difference here came, however, in the area $\mu > \mu_{cr}$. Here, at a certain (countable) set of points in the continuum, while there are strong oscillations within a potential well, which indicates a significant wave reflection between G-markers, there was no reflection from the entire potential well. That confined partially standing wave is a signature of a resonant state in a finite-depth quantum well with rigid walls, most known in the case of a finite rectangular

box. The condition for them to emerge above a quantum well is a significant rigidity of the well's walls. In the limit $\mu \gg \mu_{cr}$, their energies in the continuum coincide with those of a finite box, or in turn -- with the eigenstates of a box with infinitely-high walls. In optics terms, they correspond to full-transmission resonances of a Fabri-Pierrot resonator with semi-transparent mirrors. In the solid state, these states may reveal themselves during a kick-field ionization via production of spatially stratified bunches in photoelectron current, whose kinetic energies coincide with those of the resonant states, as was predicted in the work done by this PI in collaboration with his post-doc, P. L. Shkolnikov, a few years ago under previous AFOSR grant.

Potential uses or applications of 1D (or almost 1D) G-markers can be envisioned, such as (a) observation of quantum "traces" in continuum, i.e., beyond "quantum carpets" in potential wells discovered by this PI in collaboration with Wolfgand Schleich of Ulm University (Germany) a few years ago, (b) detection and control of slight changes of optical fiber parameters, (c) the diagnostics of cold underdense plasma, (d) medical surface-wave ultrasound tomography, (e) detection of the movement of near-shelf profiles of the bottom of oceans and rivers by space- or air-borne photography of the patterns of wind-driven gravitation waves, as well as (f) contour detection and tracing of submerged large moving man-made objects in the ocean.

A 2D and 3D expansion of the theory may need to be developed for other potential applications of G-markers such as (g) the "tomography" of quantum landscape in disordered solid-state at above-critical temperature, (h) a bulk tomography of opaque fluids (e.g., oil or muddy water) by using non-penetrating surface EM or acoustic waves, or of solid-state bodies (e.g., in "introvision" of computer chips, or lacunas in blobs of metallic alloys or glass), as well as (i) in plasma- and astrophysics.

2.ii. Beyond attoseconds [2]

In his previous research under the AFORS support, this PI has made pioneering contributions in the new field of sub-femtosecond and attosecond pulses, in particular by publishing a very first paper [A. E. Kaplan, "Subfemtosecond Pulses in Mode-locked "2 π"-Solitons of the Cascade Stimulated Raman Scattering", Phys. Rev. Lett. 73, 1243 (1994)] on proposed way of generation of sub-femtosecond pulses, followed up by a few papers on the subject by himself and his group. This contribution was credited, by the way, in the citation of his work in the Max Born Research Reward and Medal for 2005. After that, he with his former post-doc P. L. Shkolnikov, made next daring step by proposing, again for the first time, to look beyond those horizons by proposing the way of generating controllable *zepto – second* (10^{-21} *s*) pulses [A. E. Kaplan and P. L. Shkolnikov, "Lasetron: a proposed source of powerful nuclear-time-scale electromagnetic bursts", Phys. Rev. Lett., 88, 074801 (2002)]. as well as couple more papers on related subjects with other members of his group.

This new direction of research is taking very few steps forward, and there was a great need to review the pilot ideas on the generation of electromagnetic (EM)-pulses much shorter than already available sub-femtosecond pulses, and outline inroads and venues into the physics of pulses much shorter than sub-femtosecond or even attosecond pulses, in particular

the zeptosecond (10^{-21} s) and even yoctosecond (10^{-24} s) pulses that may allow one to operate on QED and nuclear, as well as quark-gluon time plasma scales. This job was done by this PI in his paper [2], where he also outlined the entire time-scale available in the existing universe, down to the ultimately short the so called Planck time, around 10^{-43} seconds, which is the time-scale of Big Bang, and the most significant time scale posts on the road to it. In his work [2], this PI also proposed specific mechanisms and objects for generation of those "beyond-attosecond" pulses, one of which is to use highly ionized atoms of heavy elements of the periodic table, including uranium hydrogen-like atoms that might allow one to go beyond 10^{-20} second.

2.iii. Highly-multiple hysteresises of reflection and transition in plasma layers [3]

In this PI's research, some of the recurrent themes are relativistic effects in electrons and related optical nonlinearities, and optical optical multi-stability effects in various systems, including single electrons. The first work in this direction was his prediction of a bistable/hysteretic cyclotron resonance of a single electron in a trap [A. E. Kaplan, "Hysteresis in cyclotron resonance based on weak-relativistic mass-effect of the electron," Phys. Rev. Lett., 48, 138 (1982)]; this hysteretic resonance has been 4 year later observed experimentally by the Dehmelt group (Dehmelt later got a Nobel Prize for trapping single particles, and this effect was one of very few observed with trapped electrons). This PI has later published a few papers on related effects and nonlinear relativistic optics in PRL and other journals. His work in the field is widely recognized by the research community; as an example, the citation for his OSA Max Born Award of 2005 reads: "*For Alexander E. Kaplan for seminal contributions to nonlinear interface and optical bistability effects, hysteretic resonances of a single electron and physics of sub-femtosecond pulses.*"

In his recent work [3] he has shown that an overdense plasma layer irradiated by intense light can exhibit dramatic nonlinear-optical effects due to a relativistic mass-effect of free electrons: highly-multiple hysteresises of reflection and transition, and emergence of immobile waves of large amplitude. Those are trapped quasi-soliton spikes sustained by a weak pumping having a tiny fraction of their peak intensity once they have been excited first by higher power pumping. The phenomenon persists even in the layers with "soft", wash-out boundaries, as well as in a semi-infinite plasma with low absorption.

Diverse phenomena such as light reflection at a dielectric interface, under-barrier scattering of an electron in quantum mechanics, and wave propagation in waveguides, plasma, free-electron gas, and in band-gap materials, including Bose-Einstein condensate (BEC), exhibit a common critical behavior: a dramatic transition at a crossover from a traveling wave in an underlying medium to a non-propagating, evanescent wave that carry no energy. The crossover occurs in optics at the angle of total internal reflection at a dielectric interface, at a laser frequency near either a plasma frequency, or a waveguide cut-off frequency, or band-gap edge of a material; in quantum mechanics for electron scattering at the energy close to a potential plateau, etc. It can be of great significance to nonlinear optics: a nonlinear refractive index can cause a phase-transition-like effect, since a small light-induced change may translate into a

switch from full reflection to full transmission, resulting in a huge hysteresis. His new work [3] revealed a large phenomenon of highly-hysteretic nonlinear EM-propagation related to the excitation of trapped quasi-solitons (QS's) with intensity exceeding the incident one by orders of magnitude. Even a slight nonlinearity due to relativistic (RL) mass-effect of free electrons suffices to initiate the effect. Multiple (up to hundreds) hysteretic jumps between almost full reflection and full transparency may occur as the laser intensity is swept up and down. The effect can be reached with the plasma layer as thin as 5 wavelengths; it is very robust and is sustained even with washed-out, "soft" boundaries. As an example, we showed that a layer with "soft" shoulders making ~ 50 % of the entire layer length, still exhibits a few hysteresises, and a large number of self-induced resonances. Furthermore, fundamental manifestation of the phenomenon transpires in a semi-infinite plasma with a weak absorption. If the pumping intensity exceeds certain critical level, the field moves into the plasma and forms a first soliton, beyond which the field doesn't penetrate far, making thus sort of a nonlinear evanescent wave; essentially that layer makes a reflecting boundary, and a soliton is an analogy of the first half-cycle of a nonlinear standing wave. As the pumping increases, another break occurs, and now a second soliton moves in, while the point of self-reflection mover farther into plasma. Thus an initially traveling wave develops spatial oscillations due to a rising nonlinear standing wave, which eventually becomes a train of trapped quasi-solitons, the last one being a almost an ideal soliton, beyond which the field vanishes exponentially.

Lab experiment in thin plasma layer could be set up with e. g. jet of gas irradiated by a powerful CO_2 laser, with a gas density controlled to reach a crossover point at $\lambda \sim 10 \ \mu m$. This process may be also naturally occurring in astrophysical environment in plasma sheets expelled from a star (e. g. the Sun); part of the star's radiation spectrum below the initial plasma frequency is powerful enough to penetrate into the layer and be trapped as multi-soliton structure. When the layer expands, they get released as a burst of radiation, similarly to bubbles in boiling water. It is also conceivable that the multi-soliton trapping and consequent release may be part of the physics of ball-lighting subjected to a powerful radiation emitted by the main lighting discharge in mw and far infrared domains. The effect might be also used e. g. for laser fusion to deposit laser power much deeper into the fusion pallets; or for heating the ionosphere layers by a powerful rf radiation.

2.iv. Laser-excited and self-organized atomic nano-structures [4]

The work [4] by this PI and his post-doc, S. N. Volkov, has concluded their research on the so called "locsitons" in self-interacting atomic nano-lattices. It started with their theoretical discovery of nano-scale stratification of local optical fields in low-dimensional atomic lattices [Phys. Rev. Lett. *101*, 133902 (2008)] and its properties [Phys. Rev. A, *79*, 053834 (2009), and *81*, 043801 (2010)]. The work [4] presents a review on the subject, studied nonlinear modes of locsitons and optical bistability and hysteresis in the simplest and most fundamental case of two atoms, and briefly discuss potential applications of those effects. Locsitons might be put into service both in passive elements (e. g., for data transmission or in delay lines) and active elements (switches or logic elements). Locsiton-based nano-devices could thus supplement the list of alternative nano-technologies including plasmonics, which is substantially based on

surface plasmons, and spintronics. Another application of locsitons could be in nano-sensors for biological molecules and other particles and impurities. Such a nano-sensor may be built out of resonant receptor molecules, which can selectively bind target molecules or particles; otherwise, receptor molecules may be attached to particles with an optical resonance.

2.v. QED/relativistic light pressure of blackbody radiation on free electrons [5,6]

Our new research [5,6] on QED/relativistic light pressure makes inroads into new field with applications ranging from the thermodynamics of laboratory nuclear fusion to the cosmology. It attacks one of the most fundamental issues on the cross-roads of optics and electrodynamics, quantum mechanics, thermodynamics and astrophysics -- the process of how light pressure of surrounding radiation, in particular thermal or Planck radiation, brings elementary particles, in particular the lightest ones -- electrons, into equilibrium with the radiation. The issue is of great importance for the entire span of energies of particles and temperatures of radiation -- from relic radiation + cosmic rays, to controlled nuclear fusion (CNF), to nuclear explosions, to star cores, and to earlier stages of universe.

While the theory of this process -- the so called Thompson scattering and related light pressure -- for the classical domain is well known, only qualitative asymptotic estimates are known for very high energies dominated by the so called Compton/QED scattering. No general formula covering the entire spectrum of energies+ temperatures currently exists. Our fully relativistic/QED theory of particle motion damping by light pressure of an isotropic, in particular relic (or Cosmic Microwave Background, CMB) theory bridges these limits, and while based on the QED Klein-Nishina theory of electron-photon scattering, involving virtual electron-positron pair creation and annihilation, and relativistic Fokker-Planck equation, it produces explicit and amazingly simple general end results valid for the entire span of energies+temperatures. Such a theory is a timely and important development since we are already encountering the transition into Compton thermalization in the CNF physics. The theory shows that that transition is determined by the product of electron energy and radiation temperature, is currently reachable in the lab, and predicts, among other things, large acceleration of electron thermalization in the Compton domain. The result could be of substantial importance in the ongoing research efforts to reach commercially viable nuclear fusion reaction.

However, our results go far beyond the energies and temperatures available (or soon available) in the lab. Our fully relativistic/QED theory of particle motion damping by light pressure of an isotropic, in particular relic (or Cosmic Microwave Background, CMB) radiation yields analytic results for the momentum decay of an electron over entire span of energies in the Universe. The study involved an array of theoretical physics tools: the theory of Lorentz transformation of arbitrary photon spectra, the Klein-Nishina theory of high-energy photon cross-section scattering from electrons accounting for virtual pairs creation and annihilation; a relativistic Fokker-Planck equation for electron distribution, and finally -- a major cosmology formula for the temporal dynamics of redshift and CMB temperature that incorporate non-relativistic matter, radiation, and dark energy components.

In application to astrophysics and cosmology, our theory can describe the evolution of initial extremely-high-T electron distribution to low-energy spectral line for momentum span over tens orders of magnitude. A strong imprint of low-T relic radiation on high-energy spectral distribution transpires *via* formation of "*frozen non-equilibrium*" or "*forever*" state of electrons with the temperature $\sim 20K$ (including a present epoch) even as the CMB temperature goes to zero, and possible existence of narrow spectral lines as remnants of past high-T sources. Both of these results may bring up a significant change of paradigm in astrophysics and cosmology, especially if the ways are found to verify them *via* astronomic observations.

2.vi. Proposal of ultimate test of laser nuclear fusion efficiency in clusters [7]

Nuclear fusion reactions in solid-deuterium laser produced plasma were first observed 45 years ago. Recent development in laser technology and generation of neutrons brought up laser-induced explosions and ionization in very localized objects, such as deuterium clusters. A major mechanism there is Coulomb explosion, CE of e.g. deuterium (D) nano-clusters resulting in sufficiently high energy ions colliding with each other. The CE occurs when an irradiated cluster undergoes rapid and high ionization of its atoms, while free (ionized) electrons ideally almost instantly swept away by the laser. The ionic core is then torn apart by repulsive Coulomb forces resulting in CE, part of which is formation of shock-shells in expanding ionic cloud predicted by this PI and his group first in 2003 [*A. E. Kaplan, B. Y. Dubetsky, and P. L. Shkolnikov, "Shock-shells in Coulomb explosion of nano clusters", Phys. Rev. Lett., 91, 143401 (2003)*]. In that work it was shown that the ionic core in the cluster can exhibit a completely unexpected at the moment new phenomenon: the tiniest, nano-scale tsunami-like shock wave during its so called Coulomb explosion. This work is finding more and more applications; there is no publications on the subject that doesn't cite it. A greatly encouraging development is that most recently such a shock wave have been observed experimentally, and at that even with an individual cluster by the group of Kapteyn and Murnane [*D. D. Hickstein, F. Dollar, J. A. Gaffney, M. E. Foord, G. M. Petrov, B. B. Palm, K. E. Keister, J. L. Ellis, C. Y. Ding, S. B. Libby, J. L. Jimenez, H. C. Kapteyn, M. M. Murnane, and W. Xiong, Phys. Rev. Letts, 112, 115004 (2014)*].

The shock in cluster explosion held a promise of enhanced neutron output due to increased probability of $D + D$ collisions and nuclear reaction in the near vicinity of the original cluster (see the above paper by Kaplan's group, 2003). Thus the new experimental shock observation is bringing up a fundamental question of how to optimize parameters of Coulomb explosion in clusters to push it as far as possible to the goal of decades-long quest for an elusive efficient nuclear fusion for energy producing application, whereby the energy of generated neutrons exceeds that of the input. Our most recent estimates showed that the shock alone would not move the neutron output sufficiently far, and a new approach is needed.

Three major and persistent problems apparently block the road to significant advance in using laser-induced explosions in clusters: insufficient kinetic energy of most of produced ions resulting in greatly reduced collisional cross-section (typically a few KeV vs 50 -- 100KeV for maximum cross-section); too low atomic density of surrounding plasma (typically $< 10^{18} cm^{-3}$ vs $\sim 10^{23} cm^{-3}$ in solid state) resulting in low utilization of produced ions, hence insufficient

number of collisions resulting in fusion reaction vs total number of produced ions, and finally, an inevitable free electron cloud that at some point neutralizes the ion cloud and greatly hampers Coulomb explosion.

In our new work [7] we proposed the way of overcoming all of those problems. To greatly enhance output of nuclear fusion produced neutrons in a laser-initiated Coulomb explosion of Deuterium clusters, we proposed to subject the ions produced by the explosion to quasi-dc electrical pulse, to accelerate them to the energies about $70--100\,KeV$, where the $D+D$ collision cross-section is the highest. With D^+ ions shepherded then to bombard a Deuterium-rich solid-state cathode, this allows one to solve a few problems simultaneously by (a) completely removing electron cloud hindering the Coulomb explosion of ionic core, (b) utilizing up to 100% of the cluster ions to collide with the high-density packed nuclei, and (c) reaching maximum cross-section of neutron production in a single $D+D$ collision. This arrangement would not only allow to greatly enhance neutron output, but essentially provide an ultimate test of laser+cluster nuclear fusion for energy production applications, since it would result in a greatest possible neutron output from full cluster ionization. Thus, if an experiment would show that the resulting output is still substantially below the target of energy production, this would be a clear indication that the "cluster road" is not a good avenue of achieving that target. However, a viable feasible application remains for this system to be used as a compact and efficient source of neutrons. For that purpose, a proposed arrangement would offer a new promise; to explore the optimal modes of operation, we also considered the use of E-pulse acceleration for diagnostic purposes.

Bibliography: work under AFOSR grant No. F49620-11-1-0123

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[3]   A. E. Kaplan, "Optical multi-hysteresises and quasi-solitons in nonlinear plasma", Optics Express, _**21**_: 13134-13144 (2013).

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[5]   A. E. Kaplan, "Compton light pressure and spectral imprint of relic radiation on cosmic electrons", arXiv:1410.6953 (October 25, 2014), journal paper, pending

[6]   A. E. Kaplan, "Fully QED/relativistic theory of light pressure on free electrons by isotropic radiation" arXiv:1502.07279 (February 25, 2015), journal paper, pending

[7]   A. E. Kaplan, "Coulomb cluster explosion boosted by a quasi-dc pulse -- diagnostic tool and ultimate test of laser fusion efficiency in clusters" arXiv:1503.06368 (March 22, 2015), journal paper, pending

Conference papers

[C1]   A. E. Kaplan, "Rogue" giant EM-waves and multi-hysteresises in plasma, due to rela-tivistic nonlinearity", invited paper, Intl. Conference "Nonlinear Optical Materials and Applications" (NOMA'11), Cetraro, Italy (Jine 2011).

[C2]   A. E. Kaplan, "Resonantly-coupled atoms -- opto-bistable nano-elements", Frontiers in Optics (FiO'2011), September 2011

[C3]   A. E. Kaplan, "Nano-strata excitations in low-dimension atomic arrays and lattices" invited paper, Intl. Heraeus Seminar in Highlights of Quantum Optics, Hanau, Germany (May 2012)

[C4]   A. E. Kaplan and S. N. Volkov, ""Locsitons" in self-interacting atomic nanolattices", Intl. Conf., Instabilities and Control of Excitable Networks: From Macro- to Nano-Systems, Dolgoprudny, Russia (May 25-30, 2012); Proceedings of ICEN'2012: pp. 53-68

[C5]   A. E. Kaplan, "Gradient Marker -- a universal wave pattern in an inhomogeneous contin-uum" FiO'2012, Rochester (October 2012).

[C6]   A. E. Kaplan, "Gradient Markers in EM-propagation and in quantum mechanics" FRISNO'12 Nonlinear Optics Intl. Conference, Israel (February 2013).

[C7]   A. E. Kaplan, "New wave patterns in optics, quantum mechanics, and hydrodynamics" invited paper, NOMA'13 Intl. Conf., Cetraro, Italy (June 2013).

[C8]   A. E. Kaplan and S. N. Volkov, "Nano-locsitons in low-dimensional lattices" invited paper, IKONO'2013 Intl. Conf., Moscow, Russia (June 2013).

[C9]   A. E. Kaplan, "Self-Induced Multi-Resonances in Initially Opaque Plasma" Frontiers in Optics (FiO'2013), Orlando, FL (October 2013).

[C10]   A. E. Kaplan and B. Ya. Zeldovich, "QED Radiation Pressure on Electrons and Ultra-rel-ativistic "Ghost" of Relic Radiation", Frontiers in Optics (FiO'2014), Tucson, AR (October 2014).

[C11]   A. E. Kaplan, "Nonlinear Optics of Light Pressure in Cosmology", Texas A&M/Princeton workshop (May 2015)

[C12]   A. E. Kaplan, "Nonlinear Optics in Hell and Heaven: relic radiation *vs* cosmic electrons" invited paper, NOMA'15 Intl. Conf., Cetraro, Italy (June 2015).

1.

1. Report Type

Final Report

Primary Contact E-mail

Contact email if there is a problem with the report.

alkap99@yahoo.com

Primary Contact Phone Number

Contact phone number if there is a problem with the report

410-366-3056

Organization / Institution name

Johns Hopkins University

Grant/Contract Title

The full title of the funded effort.

LASER-DRIVEN ULTRA-RELATIVISTIC PLASMAS

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-11-1-0123

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Prof. Alexander E. Kaplan

Program Manager

The AFOSR Program Manager currently assigned to the award

Dr. John Luginsland

Reporting Period Start Date

06/15/2011

Reporting Period End Date

12/14/2014

Abstract

In this grant period this PI developed new research directions and made progress in his fundamental
and application research done previously for AFOSR.
This PI predicted a new optical effect whereby a media with slow spatial gradient of its characteristics is found to
exhibit a universal wave pattern ("gradient marker") in a vicinity of the maxima/minima of the gradient (Ref [1]); it is common for optics, acoustics, and quantum mechanics. Among potential applications of this effect is contour-detection and tracing of large moving submerged objects in the ocean. In his recent review [2], this PI has continued his research in the extreme ultra-short pulses beyond attosecond domain, which he pioneered in his research for AFOSR long ago by proposing the way to generate so called "zepto-second" pulses. In his paper [3], this PI predicted that an overdense plasma layer irradiated by intense light should exhibit dramatic nonlinear-optical effects due to a relativistic mass-effect of free electrons: highly-multiple hysteresises of reflection and transition,and emergence of immobile waves of large amplitude. Those are trapped

quasi-solitons in the layer sustained by a weak pumping having a tiny fraction of their peak intensity once they have been excited first by higher power pumping. The phenomenon persists even in the layers with "soft" boundaries, as well as in a semi-infinite plasma with low absorption. These effects could be used for laser fusion to deposit laser powermuch deeper into the fusion pallets; or for heating the ionosphere layers by a powerful radiation. This PI also continued (Ref. [4]) his study of laser-excited atomic nano-structures, which were predicted by him earlier in collaboration with his post-doc Volkov in the research under AFOSR grant. Two new research direction have been open by the PI recently: (1) fully QED/relativistic theory of light pressure of isotropic radiation, most of all blackbody radiation, on free electron (Refs. [5,6]), and its applications to cosmic electrons, and to the plasma under laser nuclear fusion. It generated prediction of a few interesting new effects in astrophysics and cosmology, and produced exact results on the rates of establishment of thermal equilibrium in controlled fusion reaction, and (2) a proposal how to greatly enhance output of nuclear fusion produced neutrons in a laser-initiated Coulomb explosion of Deuterium clusters, by subjecting the ions produced by the explosion to a quasi-dc electrical pulse to accelerate them to the energies where the D+D collision cross-section is the highest.

Archival (journal) publications during reported period: [1] A. E. Kaplan, "Gradient marker" -- a universal wave pattern

in inhomogeneous continuum" Phys. Rev. Lett., v. 109, 153901(1-5) (2012); [2] A. E. Kaplan, "Beyond Attoseconds",

Lasers in Engineering, UK (Special Issue: Attodynamics and Analysis with Ultra-short Laser Pulses), v. 24, 3-12 (2013);

[3] A. E. Kaplan, "Optical multi-hysteresises and quasi-solitons in nonlinear plasma", Optics Express, v. 21: 13134-

13144 (2013); [4] A. E. Kaplan and S. N. Volkov, ""Locsitons" in self-interacting atomic nanolattices", Proc. Intl. Conf.,

Instabilities and Control of Excitable Networks; Dolgoprudny, Russia, 2012, pp. 53-68. Three new papers have

recently been submitted for publication: [5] A. E. Kaplan, "Compton light pressure and spectral imprint of relic

radiation on cosmic electrons"; [6] A. E. Kaplan. "Fully QED/relativistic theory of light pressure on free electrons by

isotropic radiation", and [7] A. E. Kaplan, "Coulomb cluster explosion boosted by a quasi-dc pulse -- diagnostic tool

and ultimate test of laser fusion efficiency in clusters"; [5] and [7] – to Phys. Rev. Lett, and [6] – to "New Journal of

Physics". In addition, 10 papers were presented at various US and international conferences.

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and ultimate test of laser fusion efficiency in clusters"; [5] and [7] – to Phys. Rev. Lett, and [6] – to "New Journal of
Physics". In addition, 10 papers were presented at various US and international conferences.

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Dr. John Luginsland took over after Dr. Howard Schlossberg retired

Extensions granted or milestones slipped, if any:

No-cost extention was granted 06/15/2014 -- 12/14/2014

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

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